REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-01-

0468

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 31, 2001	Final report, 4/2000 - 4/2001

4. TITLE AND SUBTITLE
PIV DIAGNOSTICS FOR FLOW CONTROL APPLICATIONS

5. FUNDING NUMBERS
F49620-00-1-0186

6. AUTHOR(S)
Peter Vorobieff and C. Randall Truman

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

The University of New Mexico
Department of Mechanical Engineering
122 Redondo Drive NE
Albuquerque, New Mexico 87131

8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

The Air Force Office of Scientific Research
801 N Randolph St
Arlington, VA 22203-1977

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release;
distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 Words)*

We have developed a flexible instrumentation system for quantitative velocity-field measurement in a variety of experiments. The system integrates lasers, digital cameras, and a translation stage for PIV (particle image velocimetry) diagnostics. Several flows have already been investigated: the onset of vortex shedding in a water tow tank, development of a far wake in a water tow tank, Kelvin-Helmholtz instability in a wind tunnel, and a flow from a long crack in a pipe. Among the most important new results obtained with the experimental equipment provided by this grant is the following. We have determined the Reynolds number (i.e., critical velocity) at which the second wake (a regular pattern emerging in the far wake of a bluff body) is destroyed by turbulence.

20011005 137

14. SUBJECT TERMS	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

AUG 20

PIV DIAGNOSTICS FOR FLOW CONTROL APPLICATIONS

F49620-00-1-0186

Peter Vorobieff

C. Randall Truman

Jonathan Gallegos

Patrocino Chavez

Jesse Vigil
Department of Mechanical Engineering
University of New Mexico

Final Report

The equipment grant provided by the Air Force Office of Scientific Research faciklitated the purchase of equipment to develop a multi-purpose particle image velocimetry (PIV) system for studies of controlled flows. PIV has become the mainstay of modern experimental fluid dynamics. This diagnostic allows non-intrusive measurement of velocity *fields*, as opposed to point measurements. Applications involving control of turbulent flows put particularly stringent requirements on the diagnostic system due to the presence of multiple scales in the flow and the often non-trivial interaction of the control actuators with the coherent structures. To facilitate the study of a wide variety of complex flows, an integrated, computer-controlled actuation/diagnostic system was developed at the Department of Mechanical Engineering at the University of New Mexico. This system is employed in several experiments - from a study of a flow of viscous fluid from a crack in a pipe to an investigation of the influence of controls on the growth of Kelvin-Helmholtz instability in a wind tunnel. However, the first important results were acquired with this new diagnostic in a series of tow-tank experiments intended to clarify certain fundamental aspects of bluff-body wakes.

The actuation/diagnostic experimental system using equipment purchased with the grant (lasers, optics, cameras, etc) is controlled by one 750-MHz Athlon PC and allows precise control over acquisition and actuation (Figs. 1,2). A Parker Compumotors 6K4 controller driven by Motion Planner software serves both to drive the actuator (e.g., a belt drive moving a traversing system) and to trigger the digital camera. In Fig. 1, a Kodak (now Roper Scientific) Megaplus ES 4.0 camera is shown. It can acquire 15 frames per second with a 2048-pixel square resolution or 30 frames per second with a 1024-pixel square resolution. An alternative implementation[1] (Fig. 2) uses a Sony DV camcorder. The camera sends a strobe signal to a Berkeley Nucleonics digital delay generator BNC-555, which in turn triggers the Nd:YAG Gemini PIV laser. For the experiments described in this report, the pulse frequency for each laser power supply was at 15 Hz, and the delay

One of the advantages of our setup is no reliance on the computer for timing - the actuation timing and camera triggering is performed by the 6K4 controller, while the image acquisition program facilitates the storage of the image sequence in the computer memory and their subsequent save to disk. The image acquisition runs passively in the sense that there is no software trigger - the images are stored as the camera acquires them.

The acquisition/control system can be easily transported from experiment to experiment. Most of its components reside on two wheeled carts, one containing the computer and Parker Compumotors components, the other – the laser power supplies and the delay generator. The laser head is mounted on a tripod, with the laser sheet-forming optics (a combination of a spherical and a cylindrical lens) attached directly to the head. Figure 3 shows the experimental setup for PIV characterization of the flow behind a cylinder in a horizontal tow tank. The tripod with the laser head is visible on the right, the cart with the computer and Compumotor control hardware is on the left, and the tow tank is in the center. In this experiment, the actuating system is a belt drive (top of the tank) moving a traverse bar along the tank. Attached to the traverse is the digital camera and a vertically-oriented biplane hydrofoil serving as the mount for a hollow Plexiglas model of a cylinder (1 cm outer diameter, 60 cm length). The horizontal spanwise axis of the cylinder is normal to the plane of the light sheet, allowing image acquisition in the plane equidistant from the cylinder ends. The water in the tank is seeded with 60-micron polystyrene microspheres, nearly neutrally buoyant.

Two series of tow-tank experiments with PIV diagnostic have been carried out so far. The first focused on the flow behavior near the onset of vortex shedding, the second investigated flow properties in the far wake. The bluff-body wake has received a tremendous amount of attention since Bénard[2] and von Kármán[3] discovered the staggered, counter-rotating vortices alternatingly shed off the sides of a cylinder immersed in fluid flow, forming the pattern known as the vortex street. This pattern manifests itself in a wide range of scales – from submillimeter[4] to astrophysical[5], and is relevant for a vast variety of applications. However, quite a few aspects of vortex-shedding behind a bluff body still need elucidation.

The transition from a time-steady to time-periodic, vortex-shedding flow occurs at the value of Reynolds number Re=46. The onset of vortex-shedding corresponds to a supercritical Hopf bifurcation[6] and thus should be non-hysteretic. However, a recent experimental study[7] reported hysteresis in the onset of vortex-shedding behind a cylinder in a quasi-two-dimensional soap-film experiment. The flow behind a cylinder in three dimensions is neutrally stable to spanwise perturbations up to Re~170, so for a reasonably long cylinder dimensionality should not influence the character of the instability at the onset. To clarify the matter, we conducted a series of experiments where a cylinder would be towed across the tank with velocity profiles accelerating and decelerating past the Re=46 value. No hysteresis in the transition was observed, suggesting that the results of Horvath *et al.*[7] reporting hysteresis are most likely the result of an insufficiently clean experiment. Figure 3 shows instantaneous vorticity maps illustrating some of our experimental results. As the cylinder accelerates, the well-

three-dimensional results is the range of Reynolds numbers at which the second wake can be observed: in 2D, it is apparent from $Re \sim 100$ to $Re \sim 1000$, whereas in 3D the second wake is destroyed by spanwise perturbations at $Re=300$ and higher (Fig. 5).

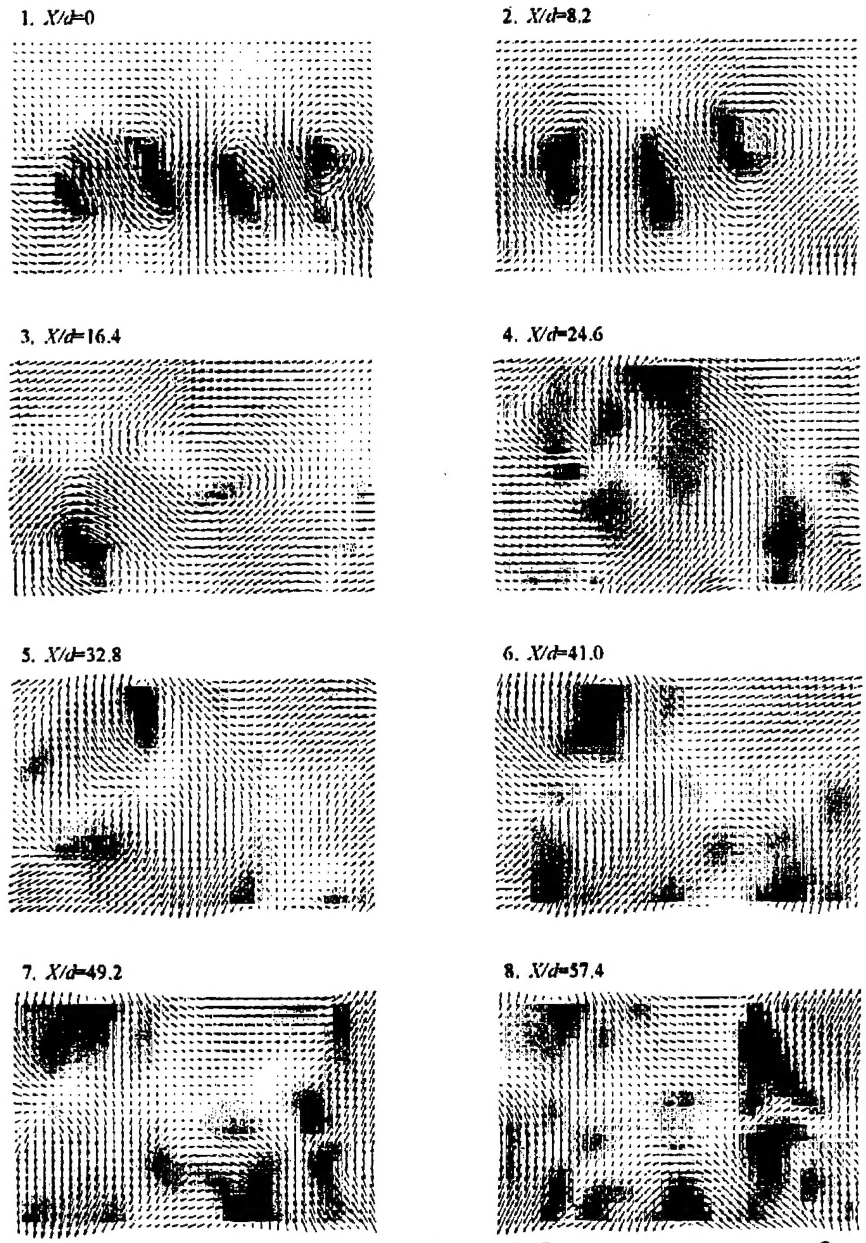

Fig. 5: Flow in the far wake of a cylinder at Re=300. Instantaneous maps of velocity components in the plane normal to the spanwise direction (arrows) and flow vorticity (red-counterclockwise, blue-clockwise). Downstream distance from the cylinder X is nondimensionalized by the cylinder diameter d.

Presently the PIV system is employed in two more experiments. The first involves a wind-tunnel study of Kelvin-Helmholtz instability. The shear layer giving rise to the instability is currently produced by putting a splitter plate in the wind tunnel and slowing down one part of the flow by putting a layer of aluminum foam into the section of the

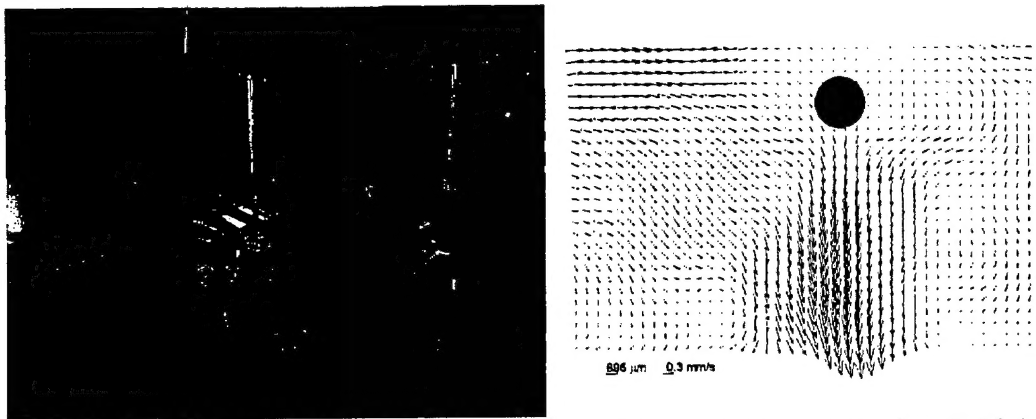

Fig. 7: Leaking pipe experimental setup (left) and instantaneous velocity field in the plane normal to the spanwise direction of the pipe (right).

References

1. P. Vorobieff, C.R. Truman, and J. Gallegos, PIV Diagnostics for Flow Control Applications, Proceedings of 2000 AFOSR Contractors' Meeting in Turbulence and Rotating Flows, AFOSR/NA, 285-289.
2. H. Bénard, Formation de Centres de Giration à l' Arrière d'un Obstacle en Mouvement. Comptes Rendus, 1908, 147:839-842.
3. Th. von Kármán and H. Rubach, Über den Mechanismus des Flüssigkeits- und Luftwiderstandes. Physikalische Zeitschrift, 1912, 13:49-59
4. P. Vorobieff and R.E. Ecke, 1999, Cylinder wakes in flowing soap films. Physcial Review E, 60:2953-2956.
5. L.F. Burlaga and J.D. Richardson, North-south flows at 47 AU: A heliospheric vortex street? Journal of Geophysical Research - Space Physics 105:10501-10507.
6. B.R. Noack and H. Eckelmann, A Global Stability Analysis of the Steady and Periodic Cylinder Wake. Journal of Fluid Mechanics, 1994, 270:297-330.
7. V.K. Horvath, J.R. Cressman, W.I. Goldburg, and X.L. Wu, 2000, Hysteresis at low Reynolds number: Onset of two-dimensional vortex shedding. Physical Review E 61:R4702-R4705.
8. S. Taneda, 1959, Downstream development of the wakes behind cylinders," Journal of the Physical Society of Japan, 14:843-848.
9. L. McMackin, R.J. Hugo, K.P. Bishop, E.Y. Chen, R.E. Pierson, and C.R. Truman, 1999, High speed optical tomography system for quantitative measurement and visualization of dynamic features in a round jet. Experiments in Fluids, 26:249-256.